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Evaluation of long-term urban transitions in a megacity's building sector based on alternative socioeconomic pathways

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ABSTRACT

Climate change has been one of the central issues for long-term transformations of cities. However, environmental loads have not been effectively taken into account for future urban plans. Specifically, possible reductions of carbon emissions from cities significantly rely on technological progress and human lifestyle changes, among other factors, which may be a barrier to estimating future environmental loads for cities. There is, therefore, urgent need for developing methods to integrate climate change policies with urban sustainable development planning. This research attempts to estimate future carbon emissions in the building sector in the megacity of Tokyo, considering the social and urban form transitions. The alternative socioeconomic pathways on an urban scale have been developed by the authors. The development of quantitative analysis methods linked with socioeconomic scenario assumptions and finding relevant parameters, also required novel thinking. In this research, influential explanatory variables for building stock changes are investigated and applied for the scenario analysis. Final results show two alternative 'sustainability' pathways that can reduce carbon emissions by approximately 15 percent compared to the Business As Usual scenario in 2050. This result encourages the development of various innovative sustainable pathways that are the most suitable for each city.

1. Introduction

There has been significant concern about how climate change policies can be integrated into real practices and implementation plans (Bulkeley & Betsill, 2003; Betsill & Bulkeley, 2006; Romro-Lankao, 2014; Rosenzweig et al., 2018). Urban planning is an important method of realising low carbon built environments (IEA, 2008; Keirstead & Shah, 2013; Rosenzweig et al., 2018). However, although integrating urban planning to achieve sustainable and low-carbon cities is strongly motivated, a methodology for developing environmental policy oriented towards long-term master planning has not been practically established.

Analysing the future of cities is obviously challenging due to the number of uncertainties. The socioeconomic pathways at the urban scale have been developed by the authors, which focused on Tokyo as a case study (Kamei, Hanaki, & Kurisu, 2016). This was developed by downscaling the global-scale Shared Socioeconomic Pathways (SSPs) which had been developed by the climate change research community (Kriegler et al., 2014; Moss et al., 2010; O'Neill et al., 2017; Riahi et al., 2017; Van Vuuren, Kriegler, & O'Neill, 2014). These socioeconomic pathways have been developed for global and national scales to bring scientific analysis to national policy developments and global climate change discussions. In addition to that, the local scale socioeconomic pathways have been identified as important for the implementation process. These different scales also enhance the cohesion of multilevel policymaking and implementations.

The significant differences in urban socioeconomic and global pathways are the additional urban form factors and more detailed lifestyle factors that are linked to concrete local implementation plans. In the urban socioeconomic scenario, urban form concepts such as monocentrism or polycentrism are determined as well as urban amenity quality and sufficient service networks, including transport links, shops, and healthcare centres. Moreover, considering the changes in sociotechnology and social value, such as those pertaining to social capital and well-being, driving forces and new urbanisation patterns also mainly focus on the urban scenario in the previous paper to determine each scenario's assumptions. Based on Tokyo's socioeconomic pathways, this research is a step toward quantitatively analysing the future changes in building stock and carbon emissions in Tokyo's building sector.

The analysis attempts to show how urban form transitions may influence carbon emissions in a city, referring to the evidence of quantitative evaluation and theoretical background in each scenario. Most important, however, is that this research applies two alternative

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sustainable pathways for Tokyo. By juxtaposing alternative pathways and quantitative results, convincing solutions can be elicited. Furthermore, key parameters for each building type, such as population, economic growth rate, building type, and emission factor, are determined by the scenario's narratives, which can secure the consistency of overall scenario evaluations. Therefore, this paper employs the socioeconomic scenario in its methodology for the persuasive quantitative analysis.

2. Analytical method

2.1. Theoretical background of three alternative socioeconomic pathways

Tokyo experienced huge urbanization during a high economic growth period from the 1960s to the 1980s. However, after the extreme growth period, Tokyo is currently experiencing a population decline and becoming an aging society, which may lead to a decrease in urban functions, specifically on the sprawling edges of the city. Additional concerns have also arisen about the deterioration of old infrastructures. Making up the core of the megacity region, Tokyo has very complex social functions and expectations for a sustainable vision.

Tokyo's long-term socioeconomic pathways include three alternative futures: a Business As Usual scenario (BAU), a Local Vitality scenario, and an Efficiency scenario.

Local Vitality scenario and Efficiency scenario belong to 'Sustainability' (SSP1) scenario in the original SSPs. The major differences among these three alternative scenarios are the transition of urban form, density of each urban cluster, building stock changes (demolition/renovation/new development) and people's lifestyle changes accompanied by social and economic transitions (see Table 1). The economic growth rate in the Local Vitality scenario and the Efficiency scenario are set at two percent, whereas in the BAU scenario it is set at one percent. This is determined in the previous paper and the significant influential factor for the following analysis. In terms of urban form, the BAU scenario does not have significant changes. However, this scenario may cause serious social disparity and physical hazards because of the old infrastructures and shrinkage of population and the economy.

In the Local Vitality scenario, on the other hand, physical capital as well as social capital that enhance local identity are emphasised and recognised as valuable assets. Therefore, recent urban form can be transformed into a polycentric compact form with remaining identical urban centres and nodes (see Fig. 1(a)). In the Efficiency scenario, ninety percent of the population is concentrated in the centre core area (23 wards) so that the urban form becomes monocentric, which is considered to be the most compact and efficient form (see Fig. 1(b)).

The key feature for this analysis is the comparison of two alternative 'Sustainability' (SSP1) scenarios. Efficiency scenario reconstructs new buildings following social market needs, and installs the latest efficiency technologies. Additionally, with population concentrated in the centre, newly developed buildings are mostly high-rise and this compact urban concept enhances energy and other resource efficiency. Such technological progress has enormous potential to develop energy efficiency and sustainable lifestyles (Newman & Kenworthy, 1996; Batty et al., 2012; Geels, 2011; Grubler et al., 2012; Hall, 2009) On the other hand, Local Vitality scenario applies more renovations and regenerations. Urban amenities are well-maintained and preserve local identities, which can increase social well-being (Glaeser, Kolko, & Saiz, 2001; Jacobs, 1961). However, renovation, regeneration, and novel ways of thinking about lifestyles can also increase efficiency (Grubler et al., 2012; Keirstead & Shah, 2013; WBGU, 2016). Therefore, these two alternative scenarios take different transition pathways to achieve different sustainable visions. The combination of qualitative societal transition analysis and quantitative analysis of social externalities, energy efficiency, and other factors can encourage synergies and trade-offs discussions among scenarios that are in line with scientific evidence. The basic definitions of scenario components and assumptions have been developed in the previous paper, and the summary and key factors are provided above (Kamei et al., 2016). This paper aims to develop a quantitative evaluation consistently linked with the scenario assumptions.

2.2. Quantitative analytical process

The detailed research steps are described as follows.

2.2.1. The building lifetime analysis

Analysing the average building lifetime requires a large amount of data of buildings, specifically the data from the period in which they are built. The Ministry of Internal Affairs and Communications (MIC) in Japan has compiled a detailed database relating to all types of buildings (the Fixed Tax Asset Rolls data (MIC), 1982-2014) and these data are divided into two categories: wooden buildings and non-wooden buildings.

First, the building scrap rate is analysed. The definition of building scrap rate is described as the rate at which buildings were demolished within an observed term (usually one year).

The scrap rate (per year) can be calculated by Eq. (1):

$$\lambda ij = \lambda i(t) = \frac{I_{i,j-1} - I_{i,j}}{I_{i,j-1}}, \quad (1)$$

where λij represents building scrap rate, which is the ratio of buildings built in year i that are scraped for one year prior to observed year j. t represents the lifetime (year) of buildings, which can calculated by the equation: $t = j - i$.

Therefore, Ii,j represents residual floor space (m^2) in observed year j of buildings which were constructed in year i.

Second, the average lifetime trend of buildings is investigated. The Kaplan-Meier method can be used for analysing approximate average building lifetime by each investigated year. (Komatsu, 1992; Komatsu, 2008; Komatsu et al., 1992; Yashiro, 1994). The building survival rate Si(t) (per year) can be calculated as one minus the building scrap rate (2):

$$Si(t) = 1 - \lambda i(t). \quad (2)$$

The cumulative building survival rate $\prod_t$ Si(t) is the building survival

Table 1
Important elements and parameters for alternative scenarios (Kamei et al., 2016).

Important elements	BAU scenario (SSP2)	Local Vitality scenario (SSP1)	Efficiency scenario (SSP1)
Population (Tokyo)	Estimation by Tokyo Metropolitan Government (Tokyo Metropolitan Government, 2014)		
Population share of 23 wards (Tokyo)	70 %		70% (2020) → 90% (2050)
Economic Growth Rate	1%	2%	
Urban form	Sprawl and functional shrink	Polycentric	Monocentric
Building updates	Relatively slow	Renovation is preferred	Scrap and built is preferred
Building energy efficiency	No change	Renovated buildings and new buildings become efficient	New buildings become efficient

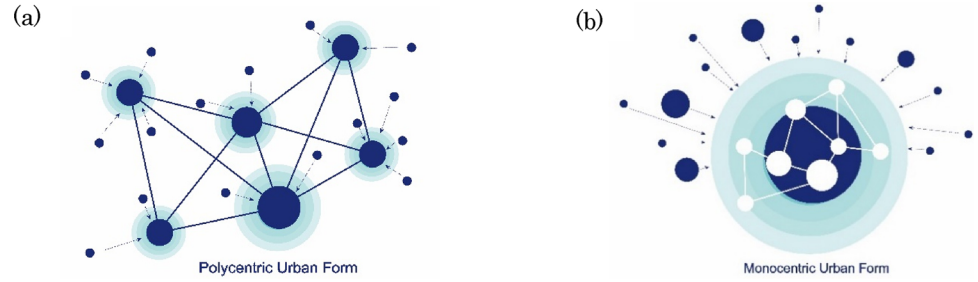

Fig. 1. The urban form concept for 'Sustainability' (SSP1) scenario: (a) Local Vitality scenario, (b) Efficiency scenario.

rate in each duration. The cumulative building survival rate can be calculated by Eq. (3). This equation explains the cumulative survival rate of buildings which are built in year i and have lifetime t:

$$\prod_{t}(1-\lambda i(t)) = \prod_{t} Si(t) \tag{3}$$

In the Kaplan-Meier method, the average of lifetime in an observed year can be recognised as the duration, which is fifty percent of the cumulative building survival rate. This method is used to analyse the building stock data of Tokyo's 23 wards. The results shows both wooden buildings and non-wooden buildings have gradually increased their average lifetimes. This result seems relevant because building technology has been significantly improved so that physical lifetime can be extended. However, a slight decline in the average lifetime of wooden buildings in recent years can be observed. This may imply that the recovery of economic vitality might have driven the scrapping of buildings. Shima, Hara, Yoshida, and Matsuhashi (2003) has analysed that a one percent increase in the economic growth rate led to a three percent increase in the building scrap rate in the past in Japan.

Therefore, the COX hazard model is used to examine the factors that influence the building scrap rate.

$$\lambda(tx) = \lambda_0(t)\exp(\beta x) = \lambda_0(t)exp(\sum_{k=1}^{m}\beta_k x_k) \tag{4}$$

where λ(t|x) represents the building scrap rate which has lifetime t. $\lambda_0(t)$ is the baseline hazard function. x is the explanatory variable and β is the coefficient which is determined by the model. In this analysis, we apply the Weibull distribution as shown in the Eq. (5):

$$\lambda_0(t) = \frac{m}{T^m}\bullet t^{m-1} \tag{5}$$

In the Weibull distribution, m > 0 is the shape parameter and T is the average lifetime (5). The COX hazard model can examine the relationship between survival time and the detailed explanatory valuables. The variations of economic growth rate and new earthquake resistance standards which use a dummy variable are tested. As a result, it is recognised that a three-year economic growth rate can be the most suitable explanatory variable to analyse the building scrap rate. This process is explained in more detail in Section 3.

2.2.2. Projections of the future building stock

In the previous analysis, the valid explanatory variable is clarified. This explanatory variable can be applied to project the future building scrap rate. In more detail, according to the analysis, the three-year economic growth rate (previous year, present year, next year) is the most relevant explanatory variables and can be applied to each scenario (Kamei et al., 2016) to estimate the future building scrap rate. Then existing building stocks are multiplied by future building scrap rate to estimate the future existing building stock of over the period until 2050.

The total future building stock, on the other hand, can be calculated by the estimating existing stocks and the new building stocks in each period. Therefore, firstly all residential building demand D_{hj} (m^2) in observation year (j) can be calculated by wooden-housing demand D_{hwj} (m^2) plus non-wooden-housing demand $D_{hnwj,}$ (m^2) as shown in the Eq. (6). Each occupancy ratio within residential building demand is determined by the current existing ratio (the Fixed Tax Asset Rolls data (MIC), 1982-2014): wooden-housing demand is 30 percent, non-wooden housing demand is 70 percent as shown in Eq. (7).

$$D_{hj} = D_{hwj} + D_{hnwj}; \tag{6}$$

$$D_{hwj} = 0.3D_{hj}\ D_{hnwj} = 0.7D_{hj}. \tag{7}$$

On the other hand, the residential building ratio of the whole wooden building stock was 97.5 percent as shown in the Eq. (8) in 2015, while the residential building ratio in the whole non-wooden building stock was 60 percent as shown in the Eq. (9) (the Fixed Tax Asset Rolls data (MIC), 1982-2014). This ratio is used for the future projections by 2050. D_{wj} and D_{nwj} represent demand for wooden buildings and non-wooden buildings in observed year (j):

$$D_{wj} = D_{hwj} / 0.975; \tag{8}$$

$$D_{nwj} = D_{hnwj} / 0.6. \tag{9}$$

Finally, new building stock of wooden buildings N_{wj} and non-wooden buildings N_{nwj} in an observed year can be estimated by the equations of each demand minus each existing stock as shown in the Eqs. (10), (11):

$$N_{wj} = D_{wj} - I_{wj}; \tag{10}$$

$$N_{nwj} = D_{nwj} - I_{nwj}. \tag{11}$$

2.2.3. The evaluation of carbon emissions

Finally, the carbon emissions in three alternative scenarios have been evaluated. Some parameters such as populations and economic growth rate are referred from the scenario story lines (Kamei et al., 2016). In addition, the carbon emission factor for each scenario is set by referring to both the conditions of the scenario story lines and the existing research results (Ikaga, Murakami, Kato, & Shiraishi, 2000; Kamei et al., 2016).

Carbon emissions in the operational phase of each scenario are evaluated. Carbon emissions are assumed to be emitted across the whole lifecycle process: scrap, rebuild, production and transportation. However, carbon emissions in the operational phase occupy more than 80 percent of the whole lifecycle of carbon emissions (Ministry of Land, Infrastructure, Transport & Tourism, 2008; Sakai, 2001). Therefore, this research evaluates the carbon emissions in the operational phase of each scenario by 2050.

For projecting carbon emissions in each scenario, the carbon emission factor per unit floor space and its improvement are defined in line with existing research results. In terms of a future projection, there are few papers that evaluate the alternative efficiency improvement rate based on the assumption of technological progress. Ikaga et al. (2000) have evaluated the carbon emissions factor in operational phase for housing and non-housing. They also evaluated the energy efficiency potential for renovation and new construction with technological progress. Based on the evaluation and assumption made by Ikaga et al.

Table 2
Carbon emission factor and its improvement efficiency factor in alternative scenarios.

Parameters	BAUscenario (SSP2)	Local Vitality scenario (SSP1)	Efficiency scenario (SSP1)
Carbon emission factor per unit floor space	Housing: 37.2kgCO_2/m^2 (Ikaga et al., 2000) Non-housing: 40.6kgCO_2/m^2 (Ikaga et al., 2000)		
Improvement rate for renovated buildings (after 2020 by 2050)	1	0.9 (Ikaga et al., 2000)	
Improvement rate for new buildings (after 2020 by 2050)	1	0.8	0.7 (Ikaga et al., 2000)

(2000), the carbon emission factor and its improvement rate are set for each scenario (see Table 2).

3. The building lifetime analysis

Firstly, the economic growth rate (Japan Cabinet Office, 2016) and the border of before/after new earthquake resistant building standards set by the Japanese government in 1981 are picked up as explanatory variables. Then the results of economic growth rates in various years can be compared. All combinations of explanatory variables show similar coefficient of determination (R^2): wooden buildings between 0.3 and 0.4; non-wooden building between 0.7 and 0.8. However, new earthquake resistance standards show a large gap emerging between the time before and after the dummy variable is applied, which does not fit the actual data for either wooden or non-wooden buildings. As a result of such examinations, a three-year average economic growth rate (previous year, present year, next year) is recognised as the most relevant fit with the real building scrap rate data, which shows trends which are most similar to the actual data. Also considering the average lifetime which can be compared with other existing literature (Komatsu, 2008), it can be seen that a three-year average economic growth rate shows the closest period: wooden around 49 years; non-wooden around 59 years. Fig. 2(a) shows the comparison between the model estimation and actual data in wooden buildings. The model estimation gradually closes to a better fit in recent years. However, a large fluctuation occurs in the economic growth rate between 2004 and 2009. In 2004, the economic growth rate in Tokyo exceeded two percent; then a large economic recession occurred in 2007. The model is directly influenced by the economic growth rate's significant increase and decline during that period. In reality, building scrap does not happen at the same rate as these extreme events, which may be why the model estimations fit the data less closely from 2004 to around 2009; however, the fit is reasonable. On the other hand, Fig. 2(b) shows the same comparison in non-wooden buildings. In recently observed years, the model estimation is closely fitted to the real data. The non-wooden buildings were less influenced by the extreme economic fluctuation between 2004 and 2009.

4. The projection of future building stock

In this projection, the theory of three future scenarios plays a significantly important role in estimating the building stock changes. The key parameters such as population and economic growth rate come from the scenarios (Kamei et al., 2016). The total population in Tokyo by 2050 is projected by the Tokyo Metropolitan Government (Tokyo Metropolitan Government, 2014). However, each scenario evolves toward different urban forms, therefore the population density in the urban core is different. The population is set as seventy percent (approximately the same rate as at present) living in 23 wards in the BAU scenario and Local Vitality scenario, whereas the Efficiency scenario increases from seventy percent in 2020 to ninety percent in 2050 in line with the large movements from suburbs to the centre core towards compact urban form. As for the economic growth rate, the BAU scenario is set as one percent per year and two percent per year is set for the Local Vitality scenario and the Efficiency scenario which were defined by the previous paper (see Table 1).

The building scrap rate and new building demand are also specific to each scenario. In the BAU scenario, building scrap will occur at a similar frequency as the recent situation. On the other hand, in the Local Vitality scenario, people tend to preserve local identical buildings and their own memorial properties, therefore, renovation will be more preferred rather than the scrap-and-build mechanism. In the estimation, after 2020, twenty percent of the building scrap rate is replaced by the renovation rate. Therefore, the total building scrap amount is reduced which leads to long-term ethical thinking; at the same time, building performance can be improved by installing the latest efficient technologies as well as building new buildings. In the Efficiency scenario, as this scenario has a two percent economic growth rate per year, the building scrap rate is higher than in the BAU scenario. Also people are encouraged to live in the centre core area (23 wards), therefore, scrapping old buildings and constructing new buildings are promoted, which also leads to upgrading to efficient buildings. The projection of the future building scrap rate of wooden buildings and non-wooden buildings by 2050 are shown in Appendix A.

Figs. 3 and 4 show the results of building stock changes by 2050 in wooden buildings and non-wooden buildings. Due to the huge population concentration in the Efficiency scenario, both wooden stocks and non-wooden stocks will be highly increased compared to the other two scenarios. Considering the differences of economic growth rate, the Local Vitality scenario and Efficiency scenario are supposed to have higher promotion of building stock changes compared to the BAU scenario. However, specifically in the case of the Local Vitality scenario, the increase in renovations extends the potential building lifetime, which keeps the building scrap speed slower.

In the case of wooden building stock (Fig. 3), assuming the increasing high-rise apartments in the Efficiency scenario, the ratio between wooden buildings and non-wooden buildings should be carefully decided. Recently, building technology of wooden buildings has been significantly improved, and also local wooden buildings are more encouraged for new construction in Japan. Due to these reasons, in the scenarios the ratio of wooden buildings and non-wooden buildings has stayed the same as it is currently.

5. The evaluation of carbon emissions

Fig. 5 represents the results of carbon emissions in each scenario by 2050. According to the building stock change analysis in Section 4, the amounts of building stock in the BAU scenario and the Local Vitality scenario are similar. However, owing to progress in efficiency, upgrading building specifications, and applying the latest efficient technologies, carbon emissions in the Local Vitality scenario can be significantly reduced compared to the BAU scenario toward 2050. On the other hand, even though the increasing population density caused enormous expansion of building floor space in the Efficiency scenario, total carbon emissions stay around a similar level as in the BAU scenario, which means carbon emissions per capita have made significant reductions in the Efficiency scenario.

Fig. 6 shows the carbon emissions per capita in each scenario by 2050. The Efficiency scenario provides the least emissions per capita in 2050. However, importantly, Local Vitality can also achieve a similar level of reductions as the Efficiency scenario by maintaining the current existing urban form and applying more renovation technologies. This result explains that without dramatic urban form transitions and huge scrap and build practices, significant carbon reductions can be realized by the renovations. Therefore, in terms of achieving a carbon emissions reduction target, some alternative pathways should be carefully considered.

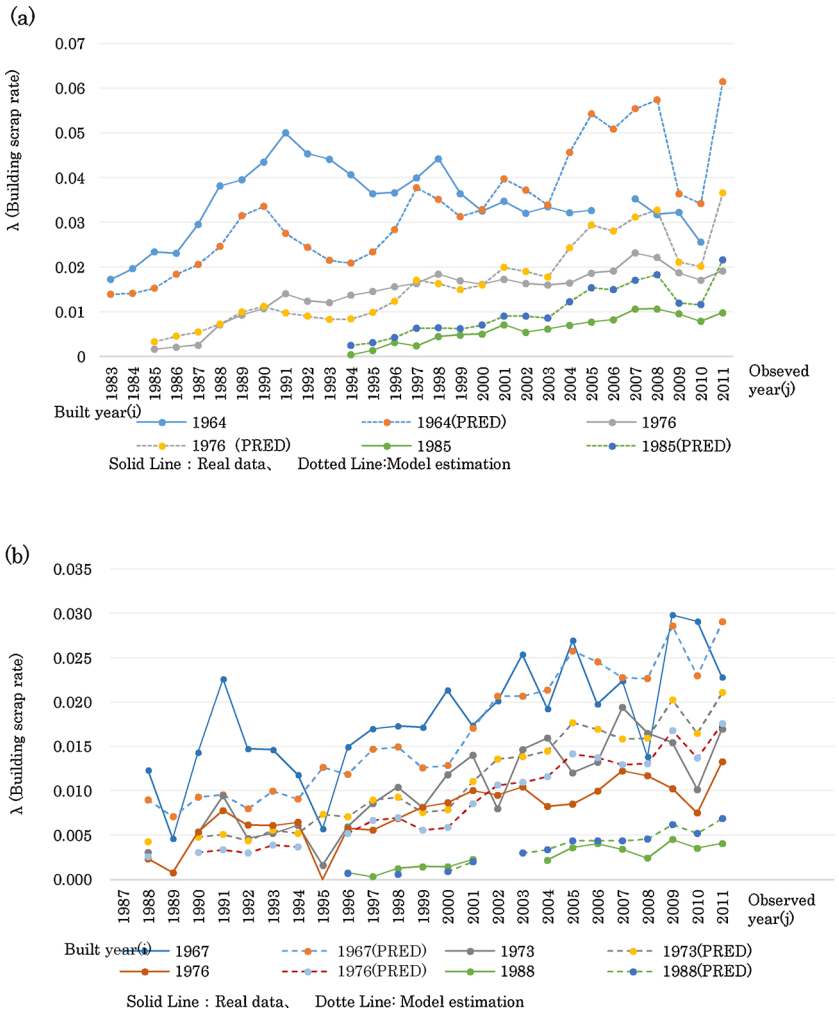

Fig. 2. The comparison of building scrap rate between model estimation and real data. (a) Wooden building, (b) Non-Wooden building. Data source: Ministry of Internal Affairs and Communications Japan (1982–2014), Japan Cabinet Office.

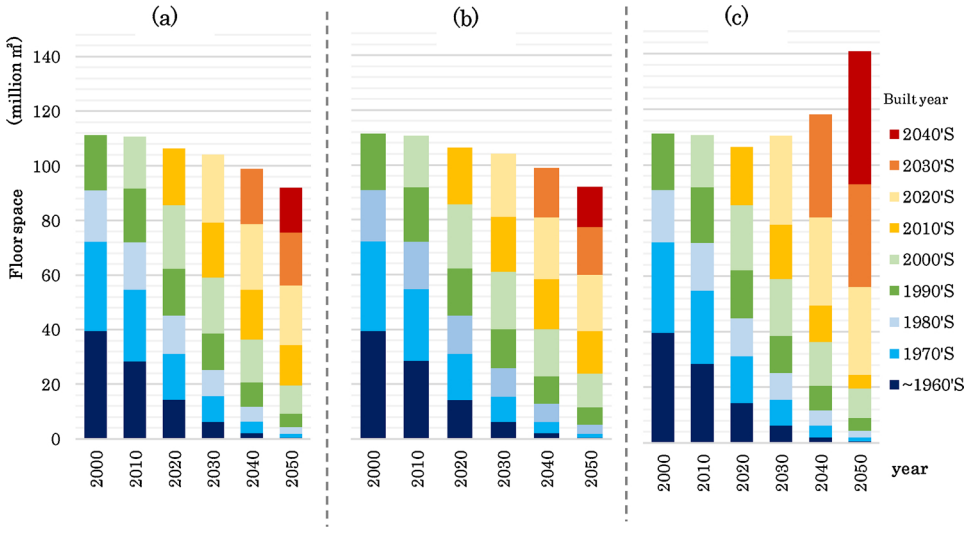

Fig. 3. The projection of future building floor space by 2050: Wooden building in 23 Wards, Tokyo. (a) BAU scenario (b) Local Vitality scenario (c) Efficiency scenario.

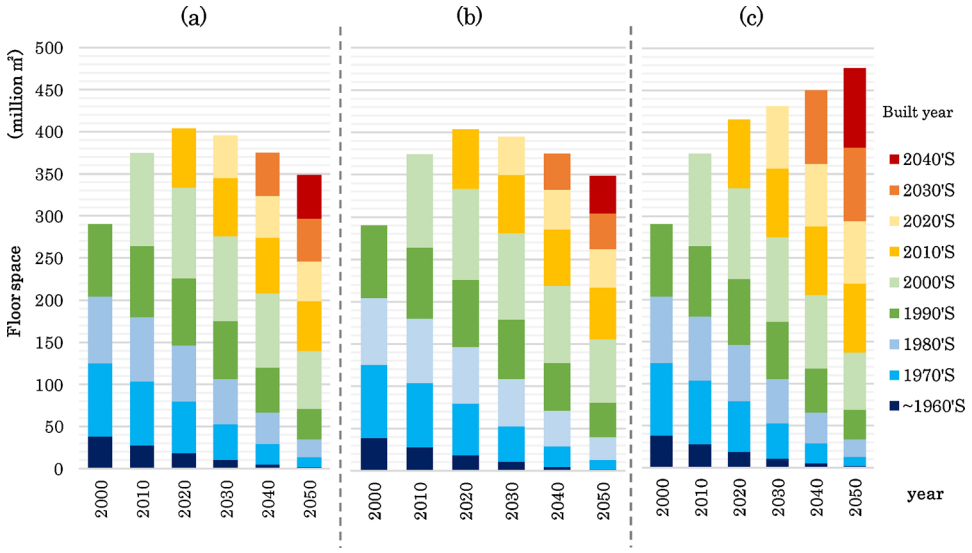

Fig. 4. The projection of future building floor space by 2050: Non-wooden building in 23 Wards, Tokyo. (a) BAU scenario (b) Local Vitality scenario (c) Efficiency scenario.

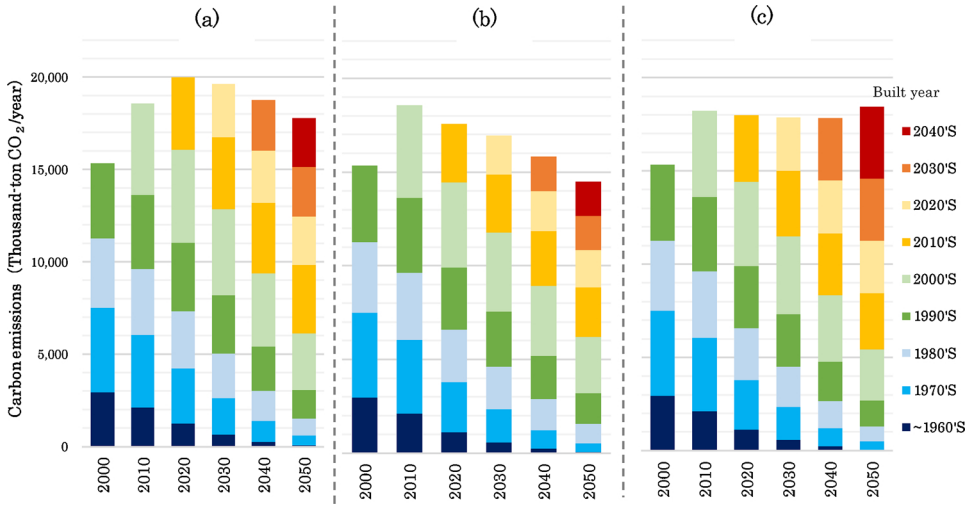

Fig. 5. The projection of carbon emissions by 2050: Total (Wooden + Non-wooden building) in 23Wards, Tokyo (a) BAU scenario (b) Local Vitality scenario (c) Efficiency scenario.

6. Discussions and conclusions

The aim of this research is to evaluate the potential for carbon emission reduction based on socioeconomic pathways. The importance of the analysis is also found in the examination of two alternative sustainable pathways. This study shows that both alternative sustainable pathways can achieve carbon emission reductions of more than 15 percent by 2050 compared to the BAU case by applying various urban transitions. Therefore, in terms of emission reduction, both scenario components can be considered possible pathways.

If total carbon emissions, however, are not significantly different, what can be a strong driver to determine the long-term future direction? The economic growth rate also has influenced the building scrap rate and promoted new construction. However, explanatory variables seem to be emerging that are difficult to explain with a single parameter such as lifestyle changes; therefore, if they are combined with the scenario narrative discussions (see Kamei et al., 2016), the synergies and trade-offs in alternative sustainable visions can be comprehensively analysed. Considering the variety of lifestyles, rich culture assets, and well-balanced social capitals, the Local Vitality scenario might result in a happier society for Tokyo even though the Efficiency scenario can replace most of the new efficient infrastructures (Kamei et al., 2016).

A sustainable city, on the other hand, includes not only low-carbon principles but also other elements. Therefore, more variations of qualitative and quantitative analysis can be considered to evaluate the possible sustainable pathways.

To sum up, the overall analysis is constructed by theoretical urban transition components, including physical urban form and quantitative analysis, evaluating the future building stock changes and carbon emissions in three alternative pathways. This paper focused on examination of influential factors of building scrap rate, estimation of future building stock changes, and evaluation of carbon emissions by considering their coherence with previously developed socioeconomic pathways. These research processes have advanced discussions of how cities can achieve sustainability and possible driving forces for urban transitions.

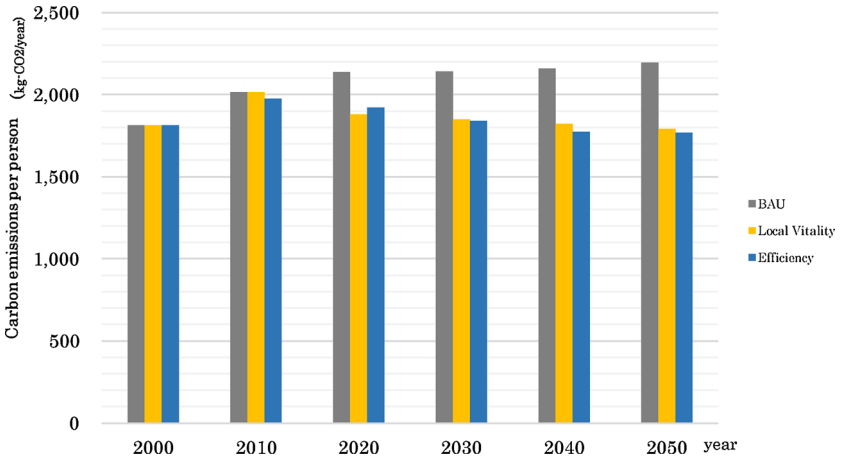

Fig. 6. The projection of carbon emissions per capita in each scenario by 2050.

Appendix A

Appendix A (a) and (b) show the projection of the future building scrap rate of wooden buildings by 2050. The real data was used up to 2012; after 2013 the model projects the scrap rate. Comparing the explanatory variables of one percent and two percent economic growth rates, the two percent rate is slightly higher than one percent. However, the impact does not seem strongly significant.

The future scrap rate of non-wooden buildings is also projected in Appendix A (c) and (d). The results show that the scrap rate under a two percent economic growth rate is higher than under one percent. The differences, however, seem moderate.

Fig. A1

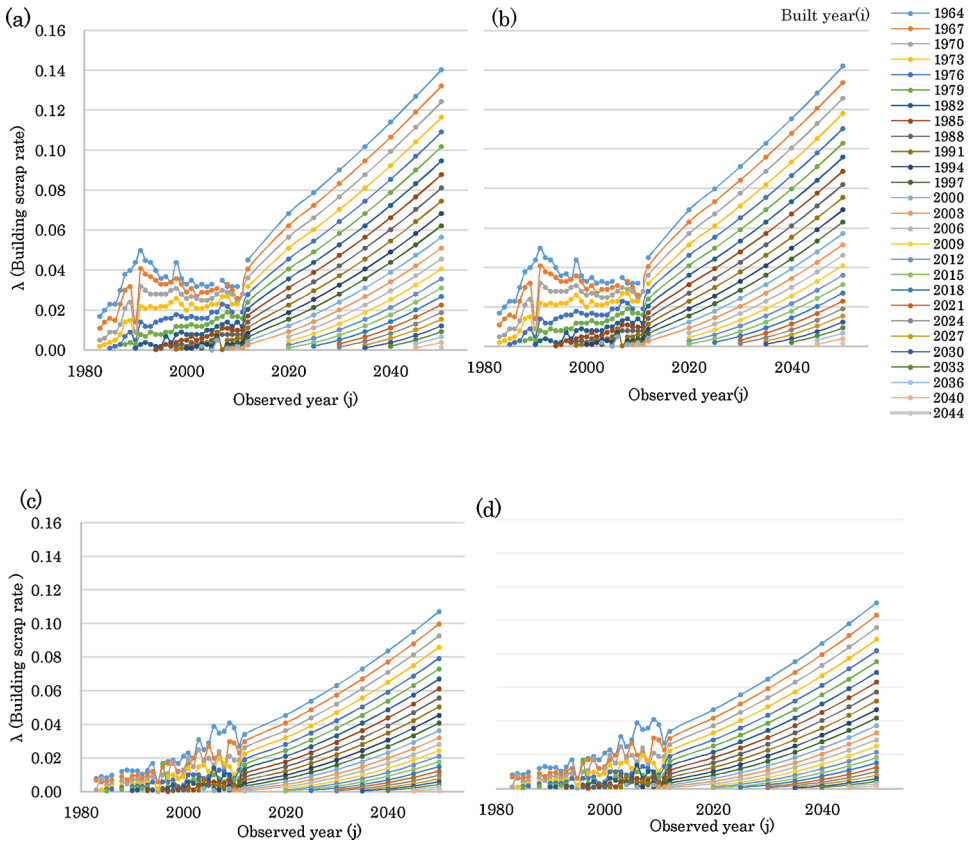

Fig. A1. The projection of future building scrap rate in wooden (a,b)and non-wooden (c, d) buildings by 2050. (a,c) Economic growth rate 1%: (b,d) Economic growth rate 2%.

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